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ERS SAR characterization of coastal polynyas in the Arctic and comparison with SSM/I and numerical model investigations

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Abstract

Coastal polynyas in the Arctic basin from the winter period (January to April) are characterized using ESA European Remote Sensing satellite (ERS)-1/2 Synthetic Aperture Radar (SAR) Precision (Precise Image, PRI) and Browse images. A SAR polynya algorithm is used to delineate open water, new ice, and young ice, and to define the size and shape of polynyas. In order to extract radiometric and contextual information in the ERS SAR PRI images, three different image classification routines are developed and applied. No in situ data have been available for verification of the polynya shapes and sizes, but one of the ice classification routines have been verified earlier using ground truth data. The SAR polynya algorithm is demonstrated to be able to discriminate between the polynya and the surrounding ice area for 85 analyzed cases. The results from the SAR algorithm are compared to ERS Browse images, passive microwave data (a recent Polynya Signature Simulation Method (PSSM), and the Bootstrap and the NASA Team ice concentration algorithms), and a numerical polynya model (NPM) forced by National Center for Environmental Predictions (NCEP) wind fields and air temperatures. The ERS SAR Browse images show a relatively good correlation with the ERS SAR PRI images (.88) while the Special Sensor Microwave Imager (SSM/I) Bootstrap and the NASA Team ice concentration algorithms both have low correlation coefficients (below .3). The PSSM calculates the polynya shape and size, and delineates open water and thin ice. For polynyas of all sizes it has a correlation of .69 compared to the SAR PRI images. For polynyas with widths greater than 10 km the correlation increases to .83. The NPM computes offshore coastal polynya widths, heat exchange, and ice production. Compared to SAR data, it overestimates the maximum size of the polynya by about 15% and has a correlation of .71 compared to the analyzed SAR PRI images. The polynyas in our main investigation area, located at Franz Josef Land, are found to be primarily wind driven. The surrounding large-scale ice drift and tidal currents have little effect on the polynya behavior. One overall conclusion from this investigation is that SAR images processed through the SAR polynya algorithm in combination with the NPM is a powerful tool for investigating and characterizing polynyas at various scales in the Arctic.

1. Introduction

Global climate models predict that a possible temperature rise will be amplified in the Arctic because of various feedback mechanisms associated with a strong coupling among the Arctic ice cover, the atmosphere, and the ocean (see e.g., Gloersen & Campbell, 1991; Manabe & Stouffer, 1993). Some of these feedback mechanisms are related to the intense heat transfer between ocean and atmosphere in polynyas and leads with large ice production and release of salt. The heat exchange from the ocean to the atmosphere can be two to three orders of magnitude larger in polynyas compared to the surrounding ice masses with an ice production of up to 5 m per event or some 50% of the seasonal mean in some areas (Winsor & Björk, 2000). Siberian shelf polynyas are capable to form 20–60% of the Arctic intermediate water (Martin & Cavalieri, 1989), and Arctic polynyas in general provide about 30% of the estimated salt flux necessary to maintain the cold halocline layer of the Arctic Ocean (Winsor & Björk, 2000). Knowledge of the distribution and frequency of coastal polynyas and leads is therefore important in order to understand large-scale climate processes in the Arctic Basin.

Satellite observations is the only possibility to monitor the Arctic ice cover on a basin wide scale. The detection potential of satellite sensors is, however, limited by their radiometric properties and their temporal and spatial resolution. Traditionally, satellite passive microwave sensors have been used to study polynyas because of their continuous temporal and spatial coverage (c.f. Cavalieri & Martin, 1985, 1994; Markus, Kottmeier, & Fahrbach, 1998; Martin & Cavalieri, 1989; Zwally, Comiso, & Gordon, 1985). Due to the typical size of polynya features (6 km average width, Winsor & Björk, 2000), a relatively high spatial resolution of the satellite sensor is required. The relatively coarse spatial resolution of passive microwave sensors (25–50 km) therefore strongly restricts the information that can be retrieved for polynya studies (i.e. they necessitate subpixel classification). There are means to improve the resolution of passive microwave data by designing a special algorithm for detecting coastal polynyas such as the Polynya Signature Simulation Method (PSSM, Markus & Burns, 1995). The PSSM has an improved spatial resolution (approximately 6 km) compared to traditional methods (e.g. the Bootstrap and the NASA Team ice concentration algorithms), which increases the possibility to detect and characterize polynyas.

The active Synthetic Aperture Radar (SAR) enables high resolution imaging (25 m spatial resolution) of the geographic region of interest independent of daylight and cloud cover. However, satellites carrying this sensor (European Remote Sensing satellite, ERS-1/2) have relatively low temporal resolution and today's SARs only use one polarization and one frequency, further limiting the detection possibilities. However, Radarsat-1, and within soon, Envisat and Radarsat-2 will have improved coverage.

This article presents one of the first approaches to study polynyas in the inner Arctic Basin during the winter months (January to April). A combination of methods is presented in order to detect the size and shape of coastal polynyas. We use both atmospheric and oceanographic data sets and a numerical model in addition to satellite observations. First, we describe routines to identify polynyas in the Arctic, by (1) ERS SAR Browse images for location of polynyas in space and time and Precise Image (PRI) images for detailed study of the polynyas, (2) Special Sensor Microwave Imager (SSM/I) images using the PSSM algorithm, and (3) a numerical polynya model (NPM). A major issue described in some detail is a new wavelet-based SAR polynya algorithm that is used to identify sizes and shapes of polynyas. We investigate to what extent the NPM and the PSSM agree with the polynya characteristics from the SAR algorithm, which we consider the most accurate identification method due to, e.g., its spatial resolution. The different methods are applied for the same geographical region of interest and within the smallest possible time interval.

4. Conclusions

Automatic polynya characterization using SAR with only VV polarization is limited primarily because open water and/or an ice class can mix with each other in the backscatter and/or texture domain. However, the SAR sensor's high spatial resolution, and the SAR polynya algorithm's addition of a "irregularity" parameter and a wavelet-based edge detection method compensate for this weakness. The SAR polynya algorithm is shown to be competitive compared to traditional methods based solely on intensity and texture measures (cf. Fig. 7) and is able to discriminate between the polynya and the surrounding ice areas for 85 analyzed cases. The algorithm consists of three independent loops in order to reduce possible errors. One of the loops (the right loop in Fig. 3) has previously been verified with overlapping aerial photography. The high-resolution SAR images can also be visually interpreted, which enables an additional control of the algorithm's performance. The SAR polynya algorithm is suitable to serve as a reference when compared to the Polynya SSM/I signature model (Markus & Burns, 1995) and an NPM (Winsor & Björk, 2000).

The NPM-estimated average offshore width of coastal polynyas in the Arctic is about 6 km. This is too small for effective monitoring with the SSM/I Bootstrap and the NASA Team ice concentration algorithms. Results from these algorithms have traditionally been used for polynya identification and classification but they give low correlation (less than .3) with the measured SAR polynya sizes (see Fig. 8). The PSSM, however, significantly increases the applicability of the SSM/I data, given the coarse resolution of approximately 6 km. When only larger-sized polynyas (>10 km) are compared, it has a thin ice correlation coefficient of .83 compared to SAR derived young ice. When all sizes of polynyas are compared (54 cases) it has an offshore width correlation of .69 compared to the SAR (see Table 1).

Numerical modeling of polynyas is effective even at small scales and in the dynamic environment typical of coastal polynyas. SAR PRI images provides the most useful data set to validate NPMs and the use of SAR in combination with an NPM significantly contributes to characterize and to gain knowledge about the dynamics of polynyas. This SAR investigation shows that the NPM-computed polynya widths (and thereby the ice and salt productions) are overestimated by approximately 15% for areas with high polynya activity. This investigation also shows that the NPM is mostly hampered by uncertainties in the atmospheric forcing and the large-scale ice drift in the basin. The NPM-computed offshore width has a correlation of .71 compared to SAR open water/new ice for 61 analyzed cases.

Future enhancement of the SAR polynya algorithm will be to combine different image representations (e.g. curvelets and wavelets) in order to improve the delineation of young ice types inside the polynya. A further operational combination of the PSSM and the SAR methods (applicable when SAR data are not available) can enhance the distinction between different new and young ice types in the PSSM model. This distinction is very important for a better understanding of the dynamics and processes in polynyas as well as for a more accurate description of the ocean to atmosphere heat exchange.

One overall conclusion from this investigation is that SAR images processed through the SAR polynya algorithm in combination with the NPM is a powerful tool for investigating and characterizing polynyas at any scale in the Arctic.

The future development of SAR satellite imagery is promising. Forthcoming SAR satellites (Envisat and Radarsat-2) will have full polarization and increased temporal and spatial coverage that will further increase the usage of this sensor. Envisat will have the same orbit configuration as ERS (35-day repeat cycle) and a maximum available swath width of 485 km (while ERS has 100 km).